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SUPPLEMENTARY DATA

Table S1. Soil nutrient and chemical properties in the 0–30 cm soil layer in the under-vine area in each treatment at the beginning (February 2021) of the experiment on field trial A (UC = untreated control; MW = mechanical weeding; SM-2.5E = mulch 2.5 L m^{-2} applied early; SM-5.0E = mulch 5.0 L m^{-2} applied early; SM-5.0L = mulch 5.0 L m^{-2} applied late). Mean ± SD (n = 4). Different letters in columns indicate significant differences among treatments (Kruskal–Wallis/Dunn with Holm correction, α = 0.05).

Soil chemical properties	UC	MW	SM-2.5E	SM-5.0E	SM-5.0L
pH	7.5 ± 0.1	7.6 ± 0.1	7.6 ± 0.0	7.5 ± 0.03	7.6 ± 0.1
$N–NH_4^+$ (kg ha^{-1})	4.5 ± 0.9	3.4 ± 0.5	4.3 ± 1.6	3.9 ± 0.6	4.5 ± 2.7
$N–NO_3^-$ (kg ha^{-1})	11.7 ± 4.0	6.0 ± 1.2	8.8 ± 1.3	8.3 ± 3.2	8.2 ± 0.8
N_{min} (kg ha^{-1})	16.1 ± 4.5^{ab}	9.4 ± 1.4^{b}	13.1 ± 2.0^{ab}	12.2 ± 2.8^{ab}	12.7 ± 3.5^{ab}
P_2O_5 (mg 100 g^{-1})	51.7 ± 6.6	56.3 ± 7.7	52.0 ± 4.8	52.3 ± 5.6	50.6 ± 6.4
K_2O (mg 100 g^{-1})	41.4 ± 3.4^{ab}	37.4 ± 4.8^{b}	45.2 ± 4.1^{ab}	41.6 ± 7.4^{ab}	42.2 ± 6.6^{ab}
Mg^{2+} (mg 100 g^{-1})	17.8 ± 1.3	18.1 ± 0.6	18.1 ± 0.4	17.8 ± 1.2	17.4 ± 0.3
C/N	10.4 ± 0.2^{ab}	10.3 ± 0.4^{ab}	10.7 ± 0.5^{ab}	10.8 ± 0.2^{a}	9.6 ± 0.2^{b}
Organic matter (%)	2.3 ± 0.3	2.2 ± 0.3	2.4 ± 0.1	2.3 ± 0.4	2.3 ± 0.1
C_{org} (%)	1.3 ± 0.2	1.3 ± 0.2	1.3 ± 0.1	1.4 ± 0.2	1.4 ± 0.1

Table S2. Soil nutrient and chemical properties in the 0–30 cm soil layer in the under-vine area in each treatment at the end (October 2022) of the experiment on field trial A (UC = untreated control; MW = mechanical weeding; SM-2.5E = mulch 2.5 L m^{-2} applied early; SM-5.0E = mulch 5.0 L m^{-2}applied early; SM-5.0L = mulch 5.0 L m^{-2} applied late). Mean ± SD (n = 4). Different letters in columns indicate significant differences among treatments (Kruskal–Wallis/Dunn with Holm correction, α = 0.05).

Soil chemical properties	UC	MW	SM-2.5E	SM-5.0E	SM-5.0L
pH	7.5 ± 0.0	7.5 ± 0.0	7.6 ± 0.1	7.6 ± 0.1	7.5 ± 0.0
$N–NH_4^+$ (kg ha^{-1})	2.9 ± 0.8	2.0 ± 0.6	3.4 ± 0.9	2.1 ± 0.6	3.0 ± 0.5
$N–NO_3^-$ (kg ha^{-1})	13.8 ± 1.1^{a}	13.7 ± 2.7^{a}	9.2 ± 1.6^{ab}	6.9 ± 3.2^{bc}	3.5 ± 1.4^{c}
N_{min} (kg ha^{-1})	13.8 ± 1.1^{a}	15.7 ± 2.2^{a}	12.6 ± 2.4^{b}	9.0 ± 3.7^{bc}	6.1 ± 1.2^{c}
P_2O_5 (mg 100 g^{-1})	45.7 ± 5.2	48.3 ± 5.7	50.4 ± 6.1	42.9 ± 5.8	48.4 ± 6.4
K_2O (mg 100 g^{-1})	44.0 ± 5.4	39.7 ± 2.1	40.5 ± 3.6	37.7 ± 4.9	38.7 ± 2.9
Mg^{2+} (mg 100 g^{-1})	18.1 ± 1.2	16.6 ± 0.7	16.8 ± 1.1	18.3 ± 3.2	16.3 ± 3.7
C/N	9.0 ± 0.4^{c}	9.0 ± 0.2^{c}	9.9 ± 0.5^{b}	10.0 ± 0.2^{b}	11.5 ± 0.5^{a}
Organic matter (%)	2.1 ± 0.2^{b}	2.0 ± 0.2^{b}	2.3 ± 0.2^{ab}	2.3 ± 0.3^{ab}	2.6 ± 0.1^{a}
C_{org} (%)	1.2 ± 0.1^{b}	1.1 ± 0.1^{b}	1.3 ± 0.1^{ab}	1.3 ± 0.1^{ab}	1.5 ± 0.1^{a}

Table S3. Soil nutrient and chemical properties in the 0–30 cm soil layer in the under-vine area in each treatment at the beginning (February 2023) of the experiment on field trial A (UC = untreated control; MW = mechanical weeding; SM-2.5E = mulch 2.5 L m^{-2} applied early; SM-5.0E = mulch 5.0 L m^{-2}applied early; SM-5.0L = mulch 5.0 L m^{-2} applied late). Mean ± SD (n = 4). Different letters indicate significant differences ($p \leq 0.05$); however, no significant differences were found in this dataset.

Soil chemical properties	UC	MW	SM-2.5E	SM-5.0E	SM-5.0L
pH	7.5 ± 0.0	7.6 ± 0.0	7.6 ± 0.0	7.6 ± 0.1	7.5 ± 0.1
N–NH_4^+ (kg ha^{-1})	4.2 ± 1.9	3.8 ± 2.0	3.4 ± 1.6	2.6 ± 1.2	3.8 ± 1.8
N–NO_3^- (kg ha^{-1})	14.8 ± 2.8	14.6 ± 1.0	15.0 ± 2.9	17.5 ± 1.1	15.2 ± 1.2
N_{min} (kg ha^{-1})	19.0 ± 4.7	18.5 ± 2.9	18.4 ± 3.9	20.1 ± 1.0	18.9 ± 3.1
P_2O_5 (mg 100 g^{-1})	28.0 ± 1.0	27.3 ± 3.2	27.3 ± 4.0	27.0 ± 2.0	29.0 ± 8.2
K_2O (mg 100 g^{-1})	29.8 ± 0.3	30.7 ± 3.2	28.0 ± 1.6	32.7 ± 5.7	33.5 ± 6.1
Mg^{2+} (mg 100 g^{-1})	17.5 ± 0.6	16.4 ± 0.5	17.1 ± 0.8	17.5 ± 1.1	16.9 ± 1.7
C/N	8.9 ± 0.3	9.0 ± 0.5	9.0 ± 0.2	9.1 ± 0.1	9.2 ± 0.5
Organic matter (%)	2.0 ± 0.1	1.9 ± 0.2	2.0 ± 0.2	2.0 ± 0.2	2.0 ± 0.2
C_{org} (%)	1.2 ± 0.1	1.1 ± 0.1	1.1 ± 0.1	1.1 ± 0.1	1.1 ± 0.1

Table S4. Soil nutrient and chemical properties in the 0–30 cm soil layer in the under-vine area in each treatment at the end (October 2024) of the experiment on field trial A (UC = untreated control; MW = mechanical weeding; SM-2.5E = mulch 2.5 L m^{-2} applied early; SM-5.0E = mulch 5.0 L m^{-2}applied early; SM-5.0L = mulch 5.0 L m^{-2} applied late). Mean ± SD (n = 4). Different letters in columns indicate significant differences among treatments (Kruskal–Wallis/Dunn with Holm correction, α = 0.05).

Soil chemical properties	UC	MW	SM-2.5E	SM-5.0E	SM-5.0L
pH	7.6 ± 0.0^{b}	7.7 ± 0.0^{a}	7.7 ± 0.1^{a}	7.8 ± 0.0^{a}	7.7 ± 0.1^{a}
N–NH_4^+ (kg ha^{-1})	2.1 ± 0.5	2.4 ± 0.6	4.6 ± 2.0	3.2 ± 1.2	3.5 ± 0.2
N–NO_3^- (kg ha^{-1})	19.7 ± 4.3^{a}	21.7 ± 7.6^{a}	11.9 ± 0.7^{ab}	8.5 ± 1.3^{b}	12.2 ± 2.7^{ab}
N_{min} (kg ha^{-1})	21.9 ± 4.6	24.1 ± 7.9	16.4 ± 1.6	11.7 ± 0.5	15.6 ± 2.6
P_2O_5 (mg 100 g^{-1})	30.4 ± 2.2	25.0 ± 4.7	24.9 ± 4.3	28.9 ± 3.3	18.1 ± 6.5
K_2O (mg 100 g^{-1})	33.9 ± 2.0	28.7 ± 4.0	27.8 ± 2.6	29.3 ± 2.3	29.1 ± 0.5
Mg^{2+} (mg 100 g^{-1})	17.7 ± 0.2	17.1 ± 0.6	17.0 ± 0.7	16.2 ± 0.2	16.6 ± 1.5
C/N	10.0 ± 0.2	10.2 ± 0.3	11.1 ± 0.3	10.8 ± 1.1	10.8 ± 0.7
Organic matter (%)	2.6 ± 0.0	2.5 ± 0.3	2.7 ± 0.3	2.5 ± 0.2	2.7 ± 0.3
C_{org} (%)	1.5 ± 0.0	1.4 ± 0.1	1.5 ± 0.2	1.4 ± 0.1	1.6 ± 0.2

Table S5. Relative abundance (%) of weed species observed in field trial A (2021) under different vineyard management treatments: (UC = untreated control; MW = mechanical weeding; SM-2.5E = mulch 2.5 L m^{-2} applied early; SM-5.0E = mulch 5.0 L m^{-2} applied early; SM-5.0L = mulch 5.0 L m^{-2} applied late). Values represent the mean relative abundance of each species, averaged across all sampling dates (May, July, September).

Species 2021	UC	MW	SM-2.5E	SM-5.0E	SM-5.0L
Cirsium arvense	0	0	1	4	0
Onobrychis viciifolia	2	0	0	0	0
Trifolium campestre	2	0	0	0	0
Fumaria officinalis	2	0	0	0	0
Poaceae spp.	14	4	2	4	15
Potentilla anserina	3	0	0	0	0
Medicago lupulina	2	0	0	0	0
Torilis arvensis	15	43	16	4	29
Papaver rhoeas	0	0	1	1	0
Veronica persica	5	0	1	4	0
Lepidium draba	27	35	64	68	44
Crepis biennis	4	0	0	0	0
Lamium purpureum	0	0	0	0	0
Achillea millefolium	0	0	0	0	0
Geranium dissectum	2	2	1	0	2
Vicia angustifolia	1	0	4	0	0
Plantago lanceolata	2	0	0	0	0
Silene vulgaris	0	0	0	0	0
Stellaria media	16	4	9	9	0
Daucus carota	0	0	0	0	4
Valerianella carinata	1	0	0	0	0
Senecia vulgaris	0	4	0	0	0
Fumaria officinalis	1	0	0	3	0
Trifolium dubium	1	0	0	0	0
Potentilla reptans	0	2	0	0	0
Sonchus asper	0	0	1	0	0
Geranium molle	0	4	0	4	6

Table S6. Relative abundance (%) of weed species observed in field trial A (2022) under different vineyard management treatments: (UC = untreated control; MW = mechanical weeding; SM-2.5E = mulch 2.5 L m^{-2} applied early; SM-5.0E = mulch 5.0 L m^{-2} applied early; SM-5.0L = mulch 5.0 L m^{-2} applied late). Values represent the mean relative abundance of each species, averaged across all sampling dates (May, July, September).

Species 2022	UC	MW	SM-2.5E	SM-5.0E	SM-5.0L
Cirsium arvense	5	2	50	27	0
Fallopia convolvulus	0	1	0	0	17
Isatis tinctoria	0	1	0	0	0
Trifolium campestre	1	0	0	0	0
Poaceae spp.	17	9	0	0	0
Trifolium dubium	1	0	1	0	0
Torilis arvensis	14	13	0	0	0
Lactuca serriola	1	1	0	0	0
Papaver rhoeas	0	3	0	0	0
Veronica persica	0	6	0	0	0
Lepidium draba	36	58	48	68	83
Crepis biennis	7	1	0	0	0
Geranium dissectum	0	1	0	0	0
Plantago lanceolata	10	0	0	0	0
Polygonum aviculare	1	0	0	0	0
Trifolium repens	1	0	0	0	0
Daucus carota	0	0	0	5	0
Sanguisorba minor	3	1	0	0	0
Ranunculus repens	2	1	1	0	0
Geranium molle	2	1	0	0	0

Table S7. Relative abundance (%) of weed species observed in field trial A (2023) under different vineyard management treatments: (UC = untreated control; MW = mechanical weeding; SM-2.5E = mulch 2.5 L m^{-2} applied early; SM-5.0E = mulch 5.0 L m^{-2} applied early; SM-5.0L = mulch 5.0 L m^{-2} applied late). Values represent the mean relative abundance of each species, averaged across all sampling dates (May, July, September).

Species 2023	UC	MW	SM-2.5E	SM-5.0E	SM-5.0L
Cirsium arvense	7	10	9	5	9
Convolvulus arvensis	1	10	6	3	3
Amaranthus spp.	3	0	0	0	0
Melilotus officinalis	0	0	0	1	0
Poaceae spp.	41	43	21	38	44
Potentilla anserina	0	0	1	0	0
Trifolium spp.	0	0	0	0	0
Torilis arvensis	11	0	0	3	0
Lactuca serriola	1	0	0	1	0
Veronica persica	0	2	6	0	0
Lepidium draba	16	27	51	49	43
Crepis biennis	2	2	0	0	0
Stellaria media	2	2	0	0	0
Polygonum aviculare	14	1	5	1	0
Geranium dissectum	1	0	0	0	0
Trifolium dubium	0	0	0	0	0
Sanguisorba minor	0	2	0	0	0
Ranunculus bulbosus	0	2	0	0	0
Potentilla reptans	0	0	0	0	1
Geranium molle	1	0	0	0	0

Table S8. Relative abundance (%) of weed species observed in field trial A (2024) under different vineyard management treatments: (UC = untreated control; MW = mechanical weeding; SM-2.5E = mulch 2.5 L m^{-2} applied early; SM-5.0E = mulch 5.0 L m^{-2} applied early; SM-5.0L = mulch 5.0 L m^{-2} applied late). Values represent the mean relative abundance of each species, averaged across all sampling dates (May, July, September).

Species 2024	UC	MW	SM-2.5E	SM-5.0E	SM-5.0L
Cirsium arvense	5	2	6	4	11
Convolvulus arvensis	1	2	6	7	4
Amaranthus spp.	12	0	0	0	0
Poaceae spp.	35	78	26	41	37
Potentilla anserina	2	0	0	0	0
Trifolium spp.	3	1	2	0	0
Torilis arvensis	8	0	0	0	0
Lactuca serriola	0	1	0	0	0
Veronica persica	3	2	0	0	0
Lepidium draba	14	12	55	47	46
Crepis biennis	0	0	1	0	0
Stellaria media	2	1	0	0	0
Vicia angustifolia	1	0	0	0	0
Melilotus officinalis	0	1	0	0	0
Polygonum aviculare	8	0	2	0	0
Geranium dissectum	0	0	0	0	0
Potentilla reptans	1	0	0	1	0
Geranium molle	5	0	0	0	0